# APPLICATION

# FOR

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**TITLE: METHOD AND APPARATUS FOR TRANSMISSION OF DATA ON MULTIPLE PROPAGATION MODES WITH FAR-END CROSS-TALK CANCELLATION**

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# METHOD AND APPARATUS FOR TRANSMISSION OF DATA ON MULTIPLE PROPAGATION MODES WITH FAR-END CROSS-TALK CANCELLATION

## Technical Field

This invention relates in general to the field of transmission of data from a well-logging tool to a data acquisition system over an electrical cable, and in particular, to a method and apparatus for improving data rate and robustness when transmitting data in multiple propagation modes by cancellation of far-end cross-talk at the receiver.

## Background of the Invention

Accurate and rapid collection and distribution of geophysical property data is a key to successful exploration and production of petroleum resources. Based on data such as electrical and nuclear properties collected in a well-bore, as well as the propagation of sound through a formation, geophysicists make an analysis useful in making many important operational decisions. The analysis includes determination of whether a well is likely to produce hydrocarbons, whether to drill additional wells in the vicinity of an existing well, and whether to abandon a well as being unproductive. Geophysicists may also use well-bore data to select where to set casing in a well and to decide on how to perforate a well to stimulate hydrocarbon flow. One method of collecting well-bore geophysical properties is by way of wireline well-logging. In wireline well-logging, a well-logging tool (also often referred to as a sonde) is lowered into a well-bore on an electrical cable, the wireline. The well-logging tool is an electrically powered measurement device that may, for example, collect electrical data, sonic waveforms that are propagated through the surrounding formation, or radioactivity counts. These measurements are usually converted to a digital form and transmitted on the wireline. Systems for transmitting data from the well-logging tool to a surface data acquisition system over a wireline cable are known as wireline telemetry systems.

One prior art wireline telemetry system is the Digital Telemetry System (DTS) of Schlumberger Technology Corporation. U.S. Pat. No. 5,838,727 (hereinafter, '727; incorporated herein by reference) describes DTS. Another wireline telemetry

system is described in co-pending U.S. Patent Application 09/471,659 which is incorporated herein by reference.

Wireline cables are primarily designed for mechanical strength and power delivery. A modern oil well may be drilled to a depth of in excess of 30,000 feet. The cable must be able to sustain the tension generated from the weight of the logging tools and the weight of the lengthy cable itself. The cable must also deliver relatively large quantities of power by alternating current or direct current to the toolstring. High frequency signal transmission properties, on the other hand, are given a lower priority. Therefore, wireline cables are not ideal conveyors of the information that is transmitted from the well-logging tools. It is desirable to provide wireline telemetry systems that can be tailored for specific or individual cables and conditions to maximally use the data delivery capabilities of a specific wireline cable.

Using a formula, known as Shannon's capacity formula, it is possible to determine a theoretical maximum channel capacity of a communication channel given a certain level of noise. Prior art well-logging telemetry systems achieve data rates that are considerably lower than the theoretical capacity. While it may not be practical (or even possible) to build a system that does achieve the Shannon capacity, it is nevertheless desirable to provide a system that achieves a data rate that comes as close as possible to the Shannon capacity for a given wireline cable.

Because of the electrical limitations on a wireline cable, the signal-to-noise ratio can be unacceptably high and significantly impact the data rate. It would be desirable to provide a system and method which overcomes the signal-to-noise ratio problems associated with wireline telemetry systems.

Modern wireline cables contain several electrical conductors, for example, 7 wires and the outer armor. Data can be simultaneously transmitted on these several conductors. The distinct combinations of conductors used are referred to herein as "propagation modes". Far-end cross-talk between the several propagation modes used simultaneously is a significant source of noise in data transmission. Far-end cross-talk is the interference between data transmitted in one propagation mode and the data transmitted in another propagation mode. Far-end cross-talk is caused by imperfections in the symmetry or insulation of the wireline cable, as well as circuitry that is used for interfacing to the cable downhole and at the surface. Far-end cross-

talk impacts both data rate and robustness of the data transmission. Cross-talk limits the available data rate and reliability. For example, cross-talk can lead to transmission failures during the progress of a logging job.

Hitherto the impact of far-end cross-talk has been avoided by precise cable design or by decreasing data rate. For example, cross-talk may be avoided by requiring near perfect electrical insulation, perfect geometry and near perfect conduction properties. Naturally, these requirements increase the cable cost and also causes the need to decommission cables relatively early due to wear. Furthermore, cross-talk may occur at the cable heads. Therefore, there is also a requirement to maintain very high insulation standards at the cable heads. Doing so can be very difficult in the harsh conditions encountered in logging jobs, e.g., high temperature and pressure.

An alternative approach to reduce the impact of far-end cross-talk is to reduce the data rate. At lower data rates the data transmission is more resilient to noise, including the noise produced by cross-talk. However, having lower data rates increases the time required for logging a well and therefore the costs associated with the logging operation and the costs due to putting other operations on hold while the well is being logged.

From the foregoing it will be apparent that there is still a need for a way to minimize the impact that far-end cross-talk has on throughput and reliability in a wireline telemetry system.

## Summary of the Invention

The deficiencies in the prior art are solved in the present invention which, in a preferred embodiment, provides a wireline telemetry system in which multiple propagation modes are used while maintaining a high data rate and robustness by cancelling out the effect of far-end cross-talk. The system thereby provides significantly greater throughput than prior art wireline telemetry systems.

The digital telemetry system of the invention has improved data rate or robustness. The digital telemetry system of the invention includes a data transmission

cable having a first end and a second end, and capable of transmitting data on at least two propagation modes. A data source is connected at the first end, has data transmission circuitry, and generates data signals on the at least two propagation modes. A receiver connected to the second end has a first receive circuitry to receive signals on a first of the at least two propagation modes and a second receive circuitry to receive signals on a second of the at least two propagation modes. An adaptive far-end cross-talk cancellation circuitry is connected to the first receive circuitry and to the second receive circuitry.

In one embodiment of the invention the adaptive far-end cross-talk cancellation circuitry adapts to changing conditions by continuously updating the cross-talk cancellation function. These updates are performed by providing a slice residual as input to a logic for updating the cross-talk cancellation function.

In another aspect the invention is a method for canceling the effect of far-end cross-talk on near-lying propagation modes. This method of digital telemetry provides improved data rate and robustness by canceling far-end cross-talk from a near-lying propagation mode. The method includes the steps of inputting a first sample on a first propagation mode; inputting a second sample on a second propagation mode; determining a cross-talk component from the second sample; and determining an output by subtracting the cross-talk component from the first sample.

Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

## Brief Description of the Drawings

Figure 1 is a schematic diagram illustrating a well-logging operation including application of the present invention;

Figure 2 is a schematic illustration of three propagation modes used on a wireline cable used in a well-logging operation as shown in Figure 1;

Figure 3 is a block diagram of the surface telemetry unit used in a well-logging operation as shown in Figure 1;

Figure 4 is a block diagram of the control logic stored in the firmware of Figure 3 for carrying out cross-talk cancellation in the time domain.

Figure 5 is a block diagram of the control logic stored in the firmware of Figure 3 for carrying out cross-talk cancellation in the frequency domain.

Figure 6 is a complex coordinate system showing a four point quadrature amplitude modulation constellation.

Figure 7 is a data flow diagram illustrating the initialization of the frequency domain equalizer coefficients and the frequency domain cross-talk cancellation coefficients.

## Detailed Description of the Preferred Embodiments

In the following detailed description and in the several figures of the drawings, like elements are identified with like reference numerals.

A note on conventions used herein, “downlink” and “uplink” refer to the direction in which data is transmitted along a wireline cable, whereas “uphole” and “downhole” refer to locations of equipment. Thus, “uphole equipment” means equipment that is located at the surface of a logging job and “downhole equipment” refers to equipment located at the logging tool end of the wireline. The word "or" is herein used as the inclusive or. If the word "or" is to be interpreted as the exclusive or, that interpretation is explicitly set forth. The preceding note is for explanatory purposes and should not be used to limit the scope of the invention.

Overview of Wireline Telemetry System According to the Invention

As shown in the drawings for purposes of illustration, the invention is embodied in a novel well-logging telemetry system for transmitting well-bore data from logging tools to a data acquisition system on the surface. A system according to the invention provides for either single carrier or multi-carrier transmission of well-logging data over multiple propagation modes and dynamic far-end cross-talk cancellation thereby achieving an improved overall data rate or more robust data transmission.

In the drawings, a preferred embodiment wireline logging application is illustrated. As shown in Figure 1, a downhole telemetry cartridge 10 is connected to a well-logging tool 16. In a well-logging operation often several tools 16 are connected into a tool string. The tools 16 communicate with the downhole telemetry circuits 10 via a bi-directional electrical interface. Typically the tools 16 are connected to the telemetry cartridge 10 over a common data bus. Alternatively, each tool may be directly connected to the telemetry cartridge 10. In one embodiment the telemetry cartridge 10 is a separate unit which is mechanically and electrically connected to the tools in the tool string. In an alternative embodiment, the telemetry cartridge is integrated into the housing of one of the well-logging tools 16.

The telemetry cartridge 10 is connected to a wireline cable 14. The tools 16, including the telemetry cartridge 10, are lowered into a well-bore on the wireline cable 14. In the preferred embodiment the wireline cable 14 is a heptacable. A heptacable consists of seven conductors – a central conductor surrounded by six conductors and an outer steel armor. A heptacable provides for several different signal propagation modes, each of which transmits signals on a specific combination of the seven conductors and armor. Figure 2 is an illustration of the T5, T6, and T7 propagation modes. In the T5 mode, the signal is propagated on conductors 201c and 201f, and the return is provided on conductors 201a and 201d. In the T6 mode, the signal is propagated on conductors 201b, 201d, and 201f, and the return is on conductors 201a, 201c, and 201e. In the T7 mode, the signal is propagated on conductor 201g and the return is on conductors 201a-201f and on the surrounding armor 203.

To utilize more of the available bandwidth of the cable 14, in a preferred embodiment of the invention at least two propagation modes are used in parallel. When data is transmitted on near-lying cable pairs it is very likely that far-end cross-talk occurs between these cable pairs.

A surface data acquisition computer 18 is located at the surface end of the wireline cable 14. The data acquisition computer 18 includes an uphole telemetry unit 12. The data acquisition computer 18 provides control of the tools and processing and storage of the data acquired by the tools. The acquisition computer 18 communicates with the uphole telemetry unit 12 via a bi-directional electrical interface.

The uphole telemetry unit 12 modulates downlink commands from the acquisition computer 18 for transmission down the cable 14 to the tools 16 and demodulates uplink data from the tools 16 for processing and storage by the acquisition computer 18.

The downhole telemetry cartridge 10 contains circuitry to modulate uplink data from the tools 16 for transmission up the cable 14 to the data acquisition computer and demodulate downlink commands from the acquisition computer for the tools. In digital telemetry systems, for example, such as the one provided by the invention, analog measurements collected by the tools 16 are converted into a digital form. That conversion may either be accomplished by the tools 16 themselves or by the telemetry cartridge 10. In a preferred embodiment of the present invention, the telemetry cartridge 10 transmits the digital data on a plurality of carriers on the wireline cable 14 to the uphole telemetry unit 12. The uphole telemetry unit 12, in turn, provides the digital data to the surface data acquisition computer 18. The uphole telemetry unit 12 and the downhole telemetry cartridge 10 cooperate in tuning the system to achieve a high data rate.

Uphole Telemetry Unit 12

Uphole Downlink Path

Figure 3 is a schematic diagram of the of the uphole telemetry unit 12. The downlink path of the uphole telemetry unit 12 consists of an acquisition computer

interface 300 and a transmitter 301. The transmitter 301 is connected to a wireline cable connection 310.

The acquisition computer interface 300 provides a bi-directional link between the uphole telemetry circuits and the other components of the acquisition computer 18. The interface to the acquisition computer 18 may be a proprietary bus or a general purpose bus (e.g., VME, ethernet). The acquisition computer interface 300 delivers downlink commands to the telemetry circuits, and this data is transmitted via the wireline cable 14 to the well-logging tools 16. The acquisition computer interface 300 is, for example, a programmable logic device or an application specific integrated circuit (ASIC).

Uphole Uplink Path

The uplink path of the uphole telemetry circuits consists of, again, the wireline cable connection 310 and a receiver 311. The receiver 311 consists of a receiver amplifier 312, a receiver signal conditioner 314, an analog to digital converter 316, a receiver DSP 320, and a receiver firmware 318, and is connected to the acquisition computer interface 300.

The receiver amplifier 312 receives data sent from the tools 16 via the downhole telemetry unit 12 and wireline cable 14. The data is received through the wireline cable connections 310. Cables with multiple conductors naturally support a variety of cable connection schemes. The output of the receiver amplifier 312 is an analog voltage waveform that represents the voltage waveform on the wireline cable 14. The receiver signal conditioner 314 applies gain and filtering to the received signal to match the amplitude and spectral content to the other telemetry circuits and to improve the processing results.

The ADC 316 converts the analog voltage waveform from the receiver signal conditioner 314 to digital samples that may be processed by digital computers such as the receiver DSP 320. The ADC 316 samples the waveform at the same frequency as that produced by the downhole telemetry cartridge 10. For example, if the downhole telemetry cartridge 10 produces samples at a rate of 300 kHz, the ADC 316 samples

the waveform at 300 kHz. In alternative embodiments, the downhole telemetry cartridge 10 produces samples at other sampling rates.

The receiver DSP 320 processes the digital samples from the ADC 316 and demodulates the sequence of samples to obtain the uplink data sent by the tools 16. The receiver DSP 320 communicates this uplink data to the acquisition computer 18 via the acquisition computer interface 300. The operation of receiver DSP 320 is controlled by instruction sequences stored, for example, in receiver firmware 318. The parameters used by the receiver DSP 320 to demodulate the uplink data may be stored in the shared memory 303.

Uphole Receiver Firmware 318

Overview

The uphole receiver firmware 318 controls many aspects of the operation of the receiver DSP during the acquisition of data via the wireline 14. Co-pending patent application 09/471,659 describes some of these operations in greater detail.

Figure 4 is a dataflow diagram of a time domain based far-end cross-talk cancellation method of the uphole receiver firmware 318 and Figure 5 is a frequency domain based far-end cross-talk cancellation method. The firmware 318 may be stored, for example, in a ROM, or an EPROM. Alternatively, the functionality provided by the DSP 320 and the firmware 318 may be implemented as an application specific integrated circuit (ASIC) or on a programmable logic array (PLA). In an alternative embodiment, the firmware 318 is replaced with software loaded into a random access memory (RAM) from a permanent storage device, EPROM or an EEPROM. That RAM may be integrated into the DSP 318. Accordingly, the methods of Figure 4 and Figure 5 may be stored in any of the aforementioned types of storage or any equivalent thereof. In most embodiments of the invention, either the time domain based method of Figure 4 or the frequency domain based method of Figure 5 is used. Therefore, the firmware 318 would in most cases only contain logic implementing one of these methods.

The uphole firmware 318 is responsible for receiving the analog signal from the logging cable and processing it appropriately so as to recover the binary data transmitted from the downhole telemetry cartridge 10.

The time domain based far end cross-talk cancellation method of Figure 4 contains two data structures for receiving demodulated output from the ADC 316, namely a T5 Delay Line 401 and a T7 Delay Line 403. The demodulated data may be, for example, demodulated using a raised cosine filter and conversion to baseband as described in the '727 patent, herein incorporated by reference.

In the example, data is transmitted on the T5 and T7 modes. In alternative embodiments other or additional propagation modes may be used.

In a preferred embodiment the Delay Lines 401 and 403 are FIFO queues. It is not required that the queues are of the same length and the number of elements in each queue is an adjustable parameter. For this discussion, each queue has *m* elements.

To produce a data stream of points from the T5 line the data points from delay line 401 are first transmitted to a linear adaptive equalizer 405. The linear adaptive equalizer 405 convolutes the *m* data points and outputs *T5TEQoutput* to a summer 415 using the equation:

$$T5TEQoutput = \sum_{i=0}^{m} CE_i \cdot T5_{(m-i)}$$

Where *CEi* is the *ith* time domain equalizer coefficient and *T5i* is the *ith* sample in the delay line 401 for T5 propagation mode. In parallel with the equalization, the T7 cross-talk component of the output *T5FEQoutput* is determined. *n* values from the T7 delay line 403 are convoluted by the Linear Adaptive Cross-talk determination logic 407. The cross-talk component from the T7 propagation mode to the T5 propagation mode of a T5 sample is:

$$CT75 = \sum_{i=l}^{n} C75_i \cdot T7_{(n-i)}$$

Where *C75i* is the *ith* coefficient for cross-talk determination and *T7i* is the *ith* T7 value in the delay line 403 for the T7 propagation mode and *l* and *n* define the range of indexes for the T7 samples used in the cross-talk determination. The setting and adjustment of the C75*i* coefficients is described below.

Conversely the cross-talk component from the T5 propagation mode to the T7 propagation mode of a T7 sample is:

$$CT57 = \sum_{i=l}^{n} C57_i \cdot T5_{(n-i)}$$

Where *C57i* is the *ith* coefficient for cross-talk determination and *T5i* is the *ith* T5 value in the delay line 401 for the T5 propagation mode and *l* and *n* define the range of indexes for the T5 samples used in the cross-talk determination. The setting and adjustment of the *C57i* coefficients is described below.

To cancel the effect of far-end cross-talk from T7 onto T5, the cross-talk component, *CT75,* determined by the cross-talk determination logic 407 is subtracted from the output of the equalizer 405, *T5TEQoutput*, using the summer 415. Conversely, to cancel the effect of cross-talk from T5 onto T7, the cross-talk component, *CT57,* determined by the cross-talk determination logic 409 is subtracted from the output of the equalizer 411, *T7TEQoutput*, using the summer 413.

The coefficients *C75i* and *C57i* are initialized during start-up and adjusted during the transmission of data.

At startup the *C75* and *C57* coefficients may be initialized to zero. This has the effect that for the first data point no cross-talk cancellation is performed. The first data points are transmitted with very few bits per symbol, e.g., one bit per symbol. Even with fairly large cross-talk, the slicing residual, the error between the signal corresponding to the expected symbol and the received signal, would be small enough to permit accurate decoding of the received signal.

In an alternative embodiment, the *C75* and *C57* coefficients are initialized using a reference signal.

Figure 6 is a complex coordinate system showing a quadrature amplitude modulation constellation of expected values 601a-d. For illustrative purpose, Figure 6 shows a four-point constellation. During the operation of the data transfer along a wireline cable, the number of constellation points used may vary. In some embodiments initial data is transmitted against a two-point constellation. During the

course of operation as the FEQ and cross-talk cancellation coefficients are fine-tuned, the number of constellation points, or bits-per-symbol, may be increased.

Returning to the example of Figure 6, each constellation point corresponds to a two-digit binary value, i.e., 00, 01, 10, or 11. Slice determination logic 417 and 419 determine which such binary value corresponds to the complex value received from summers 415 and 413, respectively. For example, if the received complex value corresponds to point 603, the slice logic would infer that the intended value is that which corresponds to point 601a, since that point lies nearest the received point. The slice logic 417 and 419 also determine the complex difference between these two points, the slice residual, 605.

The slicing residual is used to update the cross-talk cancellation coefficients input to the adaptive cross-talk component logic 407 and 409, respectively, and the linear adaptive equalization coefficients input into the linear adaptive equalizers 405 and 411, respectively. The properties of the transmission medium, the wireline, change with time. These changes may be due to temperature and also the effect of having more or less of the wireline coiled up on a reel. The update logic 421 and 423 update the linear adaptive equalizer coefficients accordingly by applying the following equation:

$$CE5i = CE5i - AlphaTEQ * (1/REF\_MAGN^2) * < T5_{(m-i)}, T5residual >$$

where,

<> is the complex scalar product, defined as

$<a+jb, c+jd> = (a-jb)*(c+jd) = (ac+bd) + j(ad-bc)$

*T5Residual[i]* is the slicing residual,

*T5Residual = T5Corr - T5IdealPoint*

where, *T5Corr* is the cross-talk corrected output from summer 415 and *T5IdealPoint* is the ideal constellation point for T5.

*AlphaTEQ* is a constant between 1 and 0, preferably close to zero, e.g., 0.001. *AlphaTEQ* balances the tracking speed of *CE5i* against the stability of the value *CE5i*.

*REF_MAGN* is the RMS magnitude of the demodulator output input to the T5 Delay Line 401.

The *C75* and *C57* coefficients are initialized to zero.

The FEXT coefficient update logic 452 updates the *C75* FEXT coefficients by

$$C75i = C75i + AlphaFEXT * (1/REF\_MAGN^2) * < T7_{(n-i)}, T5residual >$$

where,

*T5Residual* is *T5Corr - T5IdealPoint*

where *T5Corr* is the cross-talk corrected output from summer 415 and *T5IdealPoint* is the ideal constellation point for T5.

*AlphaFEXT* is a constant between 1 and 0, preferably close to zero, e.g., 0.001. The constant *AlphaFEXT* balances the tracking speed of *C75i* against the stability of the value of *C75i*.

Figure 5 is a block diagram of a method of cross-talk cancellation in the frequency domain according to an alternative embodiment of the invention. The signal streams on two propagation modes, e.g., T5 and T7, are partially equalized in the time domain by time domain equalizers 501 and 503, respectively, and transformed into the frequency domain using a Fast Fourier Transform (FFT), 505 and 507, respectively. The method of Figure 5 may be used, for example, for implementations of transmitting data on the wireline cable using discrete multi-tone modulation (DMT) and is described herein, for illustrative purposes, in that context.

The output from each FFT 505 and 507 is an array of complex values each corresponding to a value transmitted on a particular carrier on one of the propagation modes. These arrays are further equalized in the frequency domain by frequency domain equalizers 509 and 511, respectively. This equalization is performed by multiplying each array element with a corresponding coefficient, i.e.:

*T5i FEQ output = CE5i * T5i FFT output*

*T7i FEQ output = CE7i * T7i FFT output*

Figure 7 is a data flow diagram illustrating the initialization of the FEQ coefficients and the frequency domain cross-talk cancellation coefficients.

The complex FEQ coefficients *CE5i* are initialized by first estimating the complex statistical correlation of the T5 reference signal with the received T5 signal.

The normalized statistical correlation between the T5 reference signal and the received T5 signal is:

*E(<T5 reference, T5 received>/E(<T5 reference,T5 reference>)*

This quantity is obtained by calculating 701:

$$(1/N)*\frac{\sum < T5REFdata[i,n], T5FFT\_out[i,n] >}{REF\_MAGN^2}$$

This correlation is inverted 709 to initialize the FEQ coefficients as follows:

$$CE5i = \frac{(N*REF\_MAGN^2)}{\sum < T5REFdata[i,n], T5FFT\_out[i,n] >}$$

The FEQ coefficients *CE7i* are initialized by first estimating the statistical correlation of the T7 reference signal with the received T7 signal.

The normalized statistical correlation between the T7 reference signal and the received T7 signal is:

*E(<T7 reference, T7 received>/E(<T7 reference,T7 reference>)*

This quantity is obtained by calculating 707:

$$(1/N)*\frac{\sum < T7REFdata[i,n], T7FFT\_out[i,n] >}{REF\_MAGN^2}$$

This correlation is inverted 715 to initialize the FEQ coefficients as follows:

$$CE7i = \frac{(N*REF\_MAGN^2)}{\sum < T7REFdata[i,n], T7FFT\_out[i,n] >}$$

where,

$i$ is the carrier number, proportional to the frequency of each carrier

$N$ is the number of samples used for equalization, $n$ indexes those samples

$T5REFdata[i,n]$ are the complex reference constellation points for the ith carrier in the nth T5 DMT symbol

$T7REFdata[i,n]$ are the complex reference constellation points for the ith carrier in the nth T7 DMT symbol

*REF_MAGN* is the RMS magnitude of the reference data points

*T5FFT_out*$[i,n]$ is the complex output from FFT 505 for the ith carrier in the nth T5 DMT symbol

*T7FFT_out*$[i,n]$ is the complex output from FFT 507 for the ith carrier in the nth T7 DMT symbol

Returning now to Figure 5, the FEQ coefficients are updated continuously by the FEQ coefficient update logic 517 and 519. These logic modules are described in greater detail below.

If there is any far-end cross-talk between the propagation modes, the output from the frequency domain equalizers 509 and 511 contains a cross-talk component. The far-end cross-talk determination circuit 513 and 515 determines that cross-talk component for the T5 and T7 propagation modes, respectively. For the T5 data, the cross-talk component is determined by:

$$T5i\_FEXT\_com = C75i * T7iFFT\_out$$

where,

*T5i_FEXT_com* is the output from far-end cross-talk determination logic 513

*C75i* is the coefficient for canceling cross-talk from T7 to T5 on the ith carrier

*T7iFFT_out* is the output from the T7 FFT 507

Similarly, for the T7 data, the far-end cross-talk component is determined by:

$$T7i\_FEXT\_com = C57i * T5iFFT\_out$$

where,

*T7i_FEXT_com* is the output from far-end cross-talk determination logic 515

*C57i* is the coefficient for canceling far-end cross-talk from T5 to T7 on the ith carrier

*T5iFFT_out* is the output from the T5 FFT 505

The far-end cross-talk components, *T5i_FEXT_com* and *T7i_FEXT_com*, are cancelled from the equalized data by subtraction operations 521 and 523, thus the corrected output from 521 and 523 are, respectively:

*T5i_FEXT_corr = T5i_FEQ_out - T5i_FEXT_com*

*T7i_FEXT_corr = T7i_FEQ_out - T7i_FEXT_com*

Again making reference to the example of Figure 6, slice determination logic 525 and 527 determine which such binary values correspond to the complex values received from summers 521 and 523, respectively. For example, if a received complex value corresponds to point 603, the slice logic would infer that the intended value, herein also referred to as the ideal point, is that value which corresponds to point 601a, since that point lies nearest the received point. The slice determination logic 525 and 527 decode the received value to the symbol corresponding to the ideal point. The slice logic 525 and 527 also determine the complex difference between these two points, the slice residual, 605.

The slicing residual is used to update the cross-talk cancellation coefficients and the frequency domain equalization coefficients. The properties of the transmission medium, the wireline, change with time. These changes may be due to temperature and also the effect of having more or less of the wireline coiled up on a

reel. The update logic 517 updates the frequency domain equalizer coefficients for the T5 propagation mode accordingly by applying the following equation:

$$CE5i = CE5i - AlphaFEQ * (< CE5i, CE5i > / REF\_MAGN^2) * < T5FFT\_out[i], T5residual[i] >$$

where,

*T5Residual*[*i*] is the slicing residual,

$$T5Residual[i] = T5Corr[i] - T5IdealPoint[i]$$

Where, *T5Corr*[*i*] is the cross-talk corrected T5 sample on data carrier *i* output from summer 521 and *T5IdealPoint*[*i*] is the ideal constellation point for T5 data carrier i

*AlphaFEQ* is a constant between 1 and 0, preferably close to zero, e.g., 0.001. *AlphaFEQ* balances the tracking speed of *CE5i* against the stability of the value *CE5i*.

Ins A17 *REF_MAGN* is the ~~RMS~~ magnitude of *T5FEQ_out*, which in one embodiment is the same for all carrie~~rs.~~

Similarly, the update logic 519 updates the frequency domain equalizer coefficients for the T7 propagation mode by applying the following equation:

$$CE7i = CE7i - AlphaFEQ * (< CE7i, CE7i > / REF\_MAGN^2) * < T7FFT\_out[i], T7residual[i] >$$

where,

*T7Residual*[*i*] is the slicing residual,

$$T7Residual[i] = T7Corr[i] - T7IdealPoint[i]$$

Where, *T7Corr*[*i*] is the cross-talk corrected T7 sample on data carrier *i* output from summer 523 and *T7IdealPoint*[*i*] is the ideal constellation point for T7 data carrier i

*AlphaFEQ* is a constant between 1 and 0, preferably close to zero, e.g., 0.001. *AlphaFEQ* balances the tracking speed of *CE7i* against the stability of the value *CE7i*.

*REF_MAGN* is the RMS magnitude of *T7FEQ_out*.

The far-end cross-talk cancellation coefficients C75i are initialized by first estimating the statistical correlation of the T7 reference signal with the received T5 signal 703, scaled to facilitate application of the coefficient in the cancellation logic.

The scaled statistical correlation between the T7 reference signal and the received T5 signal is:

*E(<T7 reference, T5 received>/E(<T7 reference,T7 reference>)*

This quantity is obtained by calculating 703:

$$(1/N)*\frac{\sum < T7REFdata[i], T5FFT\_out[i] >}{\sum < T7REFdata[i], T7REFdata[i] >}$$

This correlation is used to initialize the cross-talk cancellation coefficients as follows 711:

$$C75i = CE5i * CE7i * (1/N) * \frac{\sum < T7REFdata[i], T5FFT\_out[i] >}{\sum < T7REFdata[i], T7REFdata[i] >}$$

The FEXT coefficient update logic 529 updates the FEXT coefficients by:

$$C75i = C75i + \\ AlphaFEXT * (< CE7i, CE7i > / REF\_MAGN^2) * < T7FFT\_out[i], T5residual[i] >$$

Where,

*T5residual*[*i*] is *T5FFT_out*[*i*] - *T5IdealPoint*[*i*]

Where *T5IdealPoint*[*i*] is the ideal constellation point for T5 data carrier i.

*AlphaFEXT* is a constant between 1 and 0, preferably close to zero, e.g., 0.0001. The constant *AlphaFEXT* balances the tracking speed of *C75i* against the stability of the value of *C75i*. *AlphaFEXT* is a parameter that an operator may adjust to obtain optimal performance given the particular noise environment received. If *AlphaFEXT* is set close to 0 there is very little adjustment of the coefficients and the far-end cross-talk correction is very stable. Conversely, if *AlphaFEXT* is set to a higher value, the far-end cross-talk correction reacts very quickly to changes in cross-talk, but becomes more jittery. For wireline applications it has been found that values for *AlphaFEXT* between 0.001 and 0.00001 are appropriate.

The far-end cross-talk cancellation coefficients *C57i* are initialized by first estimating the statistical correlation of the T5 reference signal with the received T7 signal 705, scaled to facilitate application of the coefficient in the cancellation logic.

The scaled statistical correlation between the T5 reference signal and the received T7 signal is:

$$E(<T5\ reference,\ T7\ received>/E(<T5\ reference, T5\ reference>)$$

This quantity is obtained by calculating 705:

$$(1/N)*\frac{\sum < T5REFdata[i], T7FFT\_out[i] >}{\sum < T5REFdata[i], T5REFdata[i] >}$$

This correlation is used to initialize the cross-talk cancellation coefficients as follows 713:

$$C57i = CE7i * CE5i * (1/N) * \frac{\sum < T5REFdata[i], T7FFT\_out[i] >}{\sum < T5REFdata[i], T5REFdata[i] >}$$

The FEXT coefficient update logic 531 updates the FEXT coefficients by

$$C57i = C57i + AlphaFEXT * (< CE5i, CE5i > / REF\_MAGN^2) * < T5FFT\_out[i], T7residual[i] >$$

Where,

*T7residual*[*i*] is *T7FFT_out*[*i*] - *T7IdealPoint*[*i*]

Where *T7IdealPoint*[*i*] is the ideal constellation point for T7 data carrier i.

*AlphaFEXT* is a constant between 1 and 0, preferably close to zero, e.g., 0.0001. The constant *AlphaFEXT* balances the tracking speed of *C57i* against the stability of the value of *C57i*. *AlphaFEXT* is a parameter that an operator may adjust to obtain optimal performance given the particular noise environment received. If *AlphaFEXT* is set close to 0 there is very little adjustment of the coefficients and the cross-talk correction is very stable. Conversely, if *AlphaFEXT* is set to a higher value, the cross-talk correction reacts very quickly to changes in cross-talk, but becomes more jittery. For wireline applications it has been found that values for *AlphaFEXT* between 0.001 and 0.00001 are appropriate.

The foregoing describes preferred embodiments of the invention and is given by way of example only. The invention should not be limited to such examples. For example, for illustrative purposes only, the invention has been described using two frequently used propagation modes, the T5 and T7 modes. However, the invention is equally applicable to other propagation modes and can readily be extended to implementations employing more than two propagation modes. It is well within the grasp of a person of ordinary skill, reading this disclosure, to extend the concepts herein described to such other combinations of propagation modes. The invention has been described with a particular data flow for illustrative purposes. Modifications to that dataflow are also possible and are to be considered within the scope of the invention. The invention is not limited to any of the specific features described herein, but includes all variations thereof within the scope of the appended claims.